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Durability testing of parabolic trough receivers – Overheating, thermal cycling, bellow fatigue and antireflex-coating abrasion

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Abstract

This paper describes accelerated aging tests on parabolic trough receivers. Overheating of parabolic trough receivers about 80-100 K over the nominal operating temperature is applied for accelerated aging of the absorber coating. A lifetime prediction based on the Arrhenius parameters requires extensive testing; A reduced test with heating receivers to 478 °C for 1000 hours is applied on receivers for oil fluid in order to compare heat loss and optical efficiency before and after such accelerated aging. In a further test set, such receivers are thermally cycled between 200 °C and 478 °C for 100 times. A bellow fatigue test has been developed for testing of the bellows stability for the compression and expansion. Receivers are subjected to 20,000 cycles and rested for a 24 hour waiting period. The receiver heat loss during the bellow fatigue test shall not increase more than 30 %. Durability of the antireflex coating on the glass is tested with the Taber linear abrasor using the CS-10F rubber (¾”) and MIL 12397 Eraser (¼”). Both abrasive materials proved to be suited to obtain reproducible results, although the discussion is still ongoing on which material should be used. The larger diameter of the CS-10F rubber offers the advantage that transmittance measurement with the Lambda 950/1050 spectrophotometer can be performed without the necessity for multiple abrading stripes.

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Keywords: paraboilc trough receiver; accelerated aging; overheating; thermal cycling; bellow fatigue; abrasion; AR-coating

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1. Introduction

The receiver is a key component in the parabolic trough solar thermal power plant. Hence test benches for the non-destructive measurement of thermal and optical performance of parabolic trough receivers have been developed at several institutions in the last years [1], [2], [3], [4], [5].

With the availability of these test benches focus shifted to durability testing of parabolic trough receivers. Manufacturers have a development advance in this regard, as they deal with liability demands of their customers. Archimede Solar Energy published in 2012 [6] their test bench concept of an accelerated ageing test where the glass-to-metal seal is stressed by a combination of thermal and mechanical stress.

A typical parabolic trough receiver is an absorber tube, made from stainless steel, which is coated with a spectrally selective absorber coating. A glass envelope around the absorber with an evacuated annulus reduces heat loss of the receiver. An anti-reflective (AR)-coating on the glass envelope reduces reflexion loss of solar radiation at the glass. In order to compensate for the different expansion of the absorber and the glass during heat up, bellows between the envelope and the absorber are used to form a flexible but air-tight connection.

2. Methods

Four topics of parabolic trough receiver accelerated aging are identified and corresponding tests have been developed. The topics are listed in Table 1.

Table 1. Laboratory accelerated aging tests on parabolic trough receivers at DLR

Test	Component	Aging mechanism model
Overheating test	receiver	Kinetics of chemical reactions, diffusion, desorption described by Arrhenius equation
Thermal cycling test	receiver	no model
Bellow fatigue test	receiver	aging depending on number of cycles and on temperature
AR-coating abrasion	small glass samples	field: mechanical abrasion by washing and wind-blown dust particles test: mechanical abrasion by rubber movement on coating

2.1. Overheating test

Accelerated aging of the absorber coating can be induced by overheating. Brunold et al. [7] describe a method based on the Arrhenius equation in the application on non-concentrating collectors. There the acceleration a_n of degrading processes is modelled by

$$a_n = \exp\left[\frac{E_n}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T_n}\right)\right] \quad (1)$$

with the ideal gas constant R = 8.314 J K^{-1} mol^{-1}, T_{ref} the temperature in the field, T_n the temperature at accelerated aging testing and E_n the activation energy of the aging process. These processes can be diffusion, chemical reactions or desorption.

These tests pose several challenges: a) tests have to be performed at several overheating temperatures in order to be able to identify the relevant processes, b) tests at very high temperatures might induce processes not relevant for the aging in the field, and c) tests at low temperatures take a very long time, until the test induces a measurable change in absorber coating properties.

First tests of accelerated aging of receivers have been conducted at a temperature of 478 °C with a testing time of 1000 h. Time was chosen with a limited testing duration in mind without the necessity to go to a too high temperature. Testing temperature T_n was chosed using the equation $T_n = [T_{max}(in\ K) + 10\ K] \cdot 1.1$, with T_{max} being the maximum operating temperature. This temperature is increased by 10 K in order to account for hot spots on the receiver. Testing temperature T_n is then calculated by further adding 10 %. Using 400 °C as T_{max} the equation yields 478 °C. The formula has been chosen arbitrarily in order to inflict overheating, but also to yield a temperature below typical testing temperatures in oder to allow for differences in the material system and hence in activation energy.

2.2. Thermal cycling test

Thermal cycling tests were not initially conceived to be included in these tests. However, as the overheating test bench is fully automated, thermal cycling tests could be implemented easily. Furthermore, thermal cycling is a typical product test and the parabolic trough receiver does experience regular temperature changes. In the lifetime of about 25 to 30 years in the field, which is roughly 10,000 days, the receiver at the end of an oil loop experiences about 10,000 cycles from 400 °C to 100 °C. As the overheating test bench currently is limited in heating power to 6 kW and heating speed limits of 5 K/min had to be introduced, and the test bench has no active cooling of the receiver, one temperature cycle takes about 5 hours. Hence testing time limits the number of cycles. First comparative thermal cycling tests for oil receivers have been performed with temperature cycles form 200 °C to 478 °C for 100 cycles.

2.3. Bellow fatigue test

During operation in the field the receiver experiences about 10,000 temperature cycles and therefore cycles of bellow expansion and compression. The bellow has to withstand this stress without leakage. A vacuum leak significantly increases heat loss of the receiver. Hence a test performed at Schott Solar was adapted for a general receiver design in which the bellow of a receiver is cyclically compressed and expended by a relative movement of absorber and glass envelope. During the test the absorber is heated at the position of the bellows to 400 °C. Leaks are detected by monitoring heat loss.

In the first comparative tests the receiver was exposed to 20,000 cycles. If heat loss did not increase more than 30 % during the test and in the 24 hours waiting period after the cycling, the test was considered pass. The 24-hour waiting period is used in order to be able to also detect microscopic leaks. The threshold of 30% is chosen considering experimental uncertainties in the presented test bench.

The test is not performed as a ‘test until failure’ as this might lead to a wrong incentive to manufacturers to build the bellow excessively durable.

2.4. Coating abraser test

In the field the antireflex-coating of the outer glass envelope experiences abrasion from cleaning and particle loaded wind. This degradation is simulated using a rubber, which is cyclically moved on back and forth over the surface of the glass envelope. The degradation of the coating is evaluated by transmittance measurement with a photospectrometer before and after the accelerated aging test.

2.5. Typical test succession

In conjunction with the development of the accelerated aging tests, a testing order is established in the first comparative test campaigns, compare Fig. 1. Aging of the components is detected by a change in performance; hence aging tests are framed by performance tests. In order to save on expensive performance measurements, the measurements between the overheating test and the thermal cycling test can be skipped.

The result of the bellow fatigue test is pass or fail. Hence this test is performed at the end. In first test campaigns for industry, three receivers per manufacturer went through the test succession shown in Fig. 2 in order to provide some statistics.

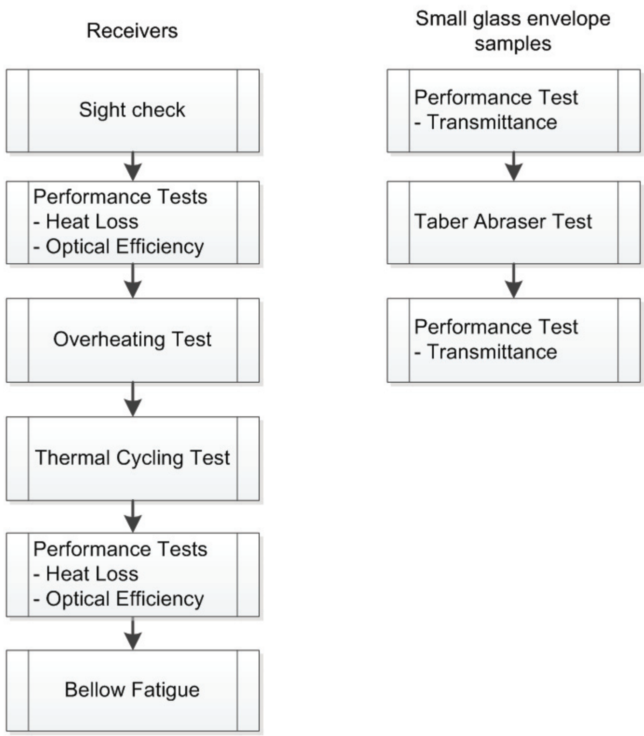

Fig. 1 Typical parabolic trough receiver accelerated aging test progression at DLR

3. Test benches for accelerated aging of receiver

Two new test benches were built for the accelerated aging of receivers, an overheating test bench and a bellow fatigue test bench, compare Fig. 2. Both test benches were based on model test benches at Schott Solar. The overheating test bench is used for both the overheating test and for the thermal cycling test. The mechanical design of the bellow fatigue test bench is currently being upgraded. Both versions are described in this paper and denoted Version 1 and Version 2.

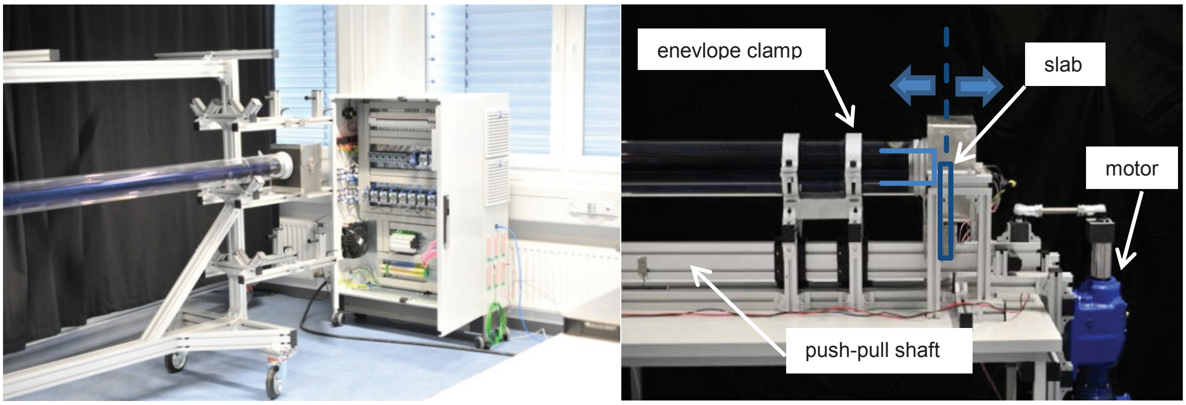

Fig. 2 (a) Overheating test bench six receiver positions (b) Bellow fatigue test bench, Version 1

3.1. Overheating test bench

The overheating test bench, also used for thermal cycling, is developed at DLR with the goal to perform lifetime predictions for parabolic trough receivers. In the test bench six receivers can be tested in parallel (Figure 2(a)).

The heating module is shown in Fig. 3. The main cartridge heater of 4060 mm in length, 30 mm in diameter and 4 kW heating power is the key component of the heating module. Rings of stainless steel are attached to a main cartridge heater in order to center the main cartridge heater within the absorber, support the weight of the main heater and provide attachment points for the thermocouples. The rings in the middle have a width of 10 mm; the rings at the ends have a width of 45 mm long as each of them houses two additional cartridge heaters of 40 mm length, 6 mm diameter and 75 W heating power. Hence three heating zones are realized. The main heater provides homogeneous heating power along the length of the receiver. The two end heaters compensate additional loss at the receiver ends. These stem in part from the additional loss at the bellows but mainly from heat loss through the axial insulation at the ends, which are shown in Fig. 2 a and Fig. 2 b. Power supply of all cartridge heaters are phase controlled modulators.

Temperature is measured with seven thermocouples at each heating module. Six type N thermocouples are connected to the data acquisition system and are listed in Table 2. The seventh thermocouple is connected to a safety switch in order to trigger safety shutdowns.

Table 2. Positions of the thermocouples at heating modules, 0°: pointing upwards, 180°: pointing downwards, safety thermocouple is not shown

Thermocouple number	Overheating test bench		Bellow fatigue test bench	
	position in mm	orientation	position in mm	orientation
1	-1930	0°	-2015	0°
2	-1930	180°	-2015	180°
3	0	0°	0	0°
4	0	180°	0	180°
5	1930	0°	2015	0°
6	1930	180°	2015	180°

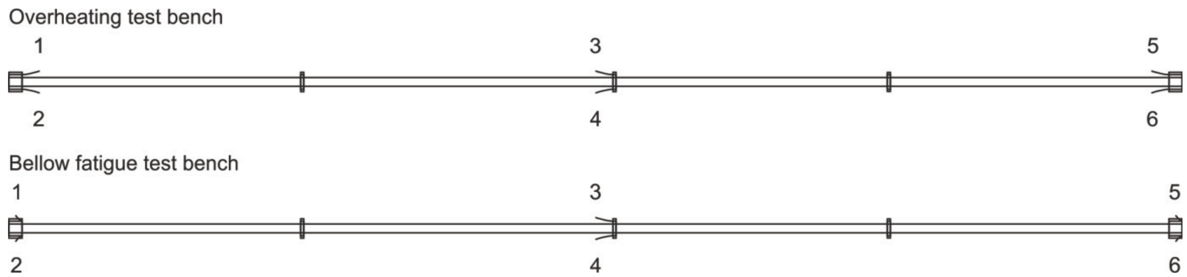

Fig. 3 Heating modules and positions of the logged thermocouples for the overheating test bench and the bellow fatigue test bench; thermocouples 1, 2, 5 and 6 are supported by end blocks, that also contain end heaters; thermocouples 3 and 4 are supported by a distances block, which are also found half way between thermocouple 1 and 3, and 3 and 5; distance blocks and end blocks define the position of the heating rod within the absorber

The data acquisition system is connected to a pc running a LabView program, which runs the algorithms for the automation of the test bench. The main heater is in-loop controlled comparing the desired temperature, e.g. 478 °C, and the mean of Thermocouple 3 and 4. The end heaters are in-loop controlled comparing the desired temperature, which is the mean of thermocouple 3 and 4 to the temperature at the ends, which is the mean of thermocouple 1 and 2, and 5 and 6 respectively. Heating power is not measured. However, the power supply control signal is used to estimate the heating power by assuming constant resistance of the heaters and a constant mains voltage.

First tests showed that it is necessary to limit heat up heat up speeds to +5 K/min. Additionally at first heat up at temperatures above 400 °C the heat up speed is limited to +0.05 K/min in order to give the getter time to absorb residual gas. Typically the temperature differences between upper and lower side of the temperature, as measured with thermocouples 3 and 4, is at the order of 4 to 7 K. This can be improved in the future by adjustment of the position of the heater in the absorber.

The parameters in use for the overheating test on oil receivers are 478 °C for 1000 hours, which is approximately 40 days.

Thermal cycling is also performed in this test bench. Thermal cycling is achieved by alternatingly heating the receiver with the heat up limit of +5 K/min and letting the receiver cool down by reducing the heating power to zero. No active cooling is currently realized. The time to perform one temperature cycle is typically 5 hours and depends primarily on the heat loss of the receiver relevant in the cool-down phase. A test with 100 cycles takes about 500 hours (20 days).

3.2. Bellow fatigue test bench

The bellow is the airtight connection of the absorber and the glass envelope. Depending on the specific receiver design, the bellow might also have to support the weight of the glass envelope. At room temperature a typical absorber has a length of 4060 mm. At operating temperature of 400 °C the absorber of the receiver expands approx. 28 mm at 400 °C, while the glass envelope hardly changes its length. As the receiver temperature is significantly reduced during the night, the bellow experiences expansion and compression every day the field is operated.

In order to simulate this expansion and compression a bellow fatigue test bench was built at DLR, compare Fig. 2 b. There the absorber is heated from room temperature to ca. 200 °C in order to achieve half the expansion (or compression, depending on the bellow design) of each bellow of approx. 14 mm. Then the envelope is cyclically moved relative to the absorber tube for that 14 mm creating alternating a fully compressed bellow at one side and a fully expanded bellow at the other side. During the test the bellow is heated to 400 °C as this is assumed to be the maximum temperature stress on the bellow. The test is typically run with one cycle per second. Failure of the bellow is defined to be detected, if heat loss increased by 30% relative to the initial value. This relatively high number is chosen according to test bench restraints: Heat loss in this test bench is not measured directly, but calculated using the resistance of the main heating rod and the analog control signal to the power supply. Furthermore, the power supply is operated in extreme part load and the resolution of the power supply beomes relevant. Also, a full venting of a modern parabolic trough receiver leads to a increase in heat loss much higher than 30%.

Aside from the mechanics of the push-pull mechanism, the test bench is similar to the overheating test bench with a control cabinet housing power supplies, safety switches and a data acquisition system, and pc with a LabView program displaying measurement data and controlling the heater powers. Also heating power is estimated by using the power supply control signal and assuming constant heater resistance and constant supply voltage.

Heating modules differ in the thermocouple positions at the ends; compare Fig. 3 and Table 2, as the temperatures of the absorber directly underneath the bellow is to be measured.

The mechanical design is currently being updated. Version 1 is shown in Fig. 2. There the glass envelope is fixed to the test bench with envelope clamps. A push-pull shaft is moved back and forth by a motor with connecting rod and eccentric shaft. Once the absorber has reached the temperature of testing, vertical slabs are connected to the linear shaft on both sides of the absorber, the motor is activated and the slabs push the absorber back and forth.

Although simple, the mechanical design has a drawback regarding the way it supports the weight of the absorber. While in the field, the absorber is supported by struts and the bellow has to support the weight of the glass envelope, in Version 1 the bellow has to support the weight of the absorber and the heating module inside the absorber. This combined weight is significantly higher than the weight of the glass envelope. It is assumed that the bellow aging of some receiver designs depends on the vertical force on the bellow. Therefore a redesign of the test bench is ongoing. The concept of the new mechanical design is shown in Fig. 4.

Again, a heating element is inserted into the receiver and the receiver is heated to ca. 200 °C in order to achieve half its maximum absorber expansion. Then the absorber clamps are firmly fixed to the test bench, connecting the absorber to the test bench and supporting the weight of the absorber and the heater module. The weight of the glass envelope is supported by the bellows. Push-pull shafts on both sides of the receiver are connected to the envelope clamp and move the envelope back and forth. Bearings allow the envelope to freely move up and down and pitch. A counter weight compensates the weight of the envelope clamp. First tests are expected to be performed with the Version 2 at the end of July 2014.

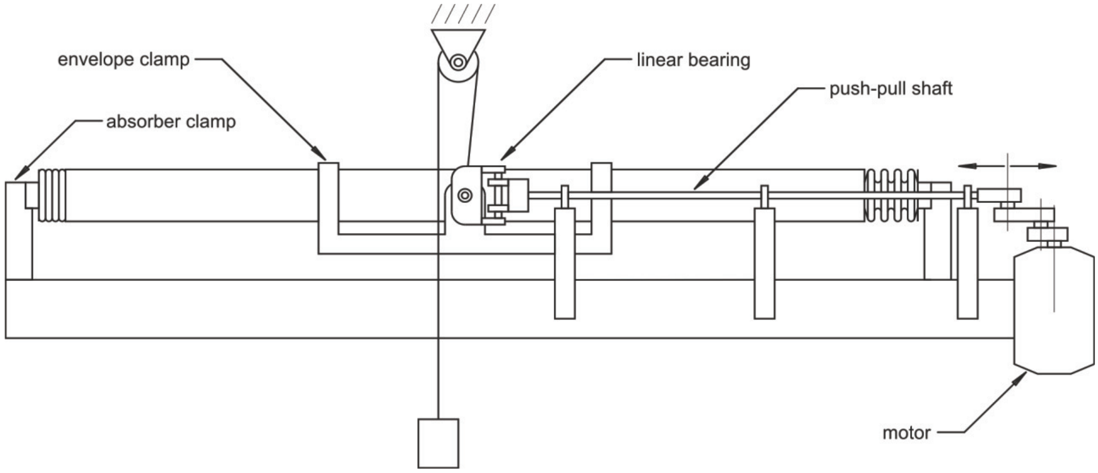

Fig. 4 Concept of bellow fatigue test bench, Version 2

4. Taber Abrasion testing of the anti-reflective coating of glass envelope tubes

During its service life time, the anti-reflective coating of glass envelope tubes suffers from abrasion due to cleaning and wind-blown dust particles. This mechanical wear of the coating is tested with the Taber Linear Abraser test, which consists in rubbing on the dry glass tube with an abrasive rubber material under a controlled normal force (see Fig. 5 a). Curved glass samples with two different anti-reflective coatings have been tested.

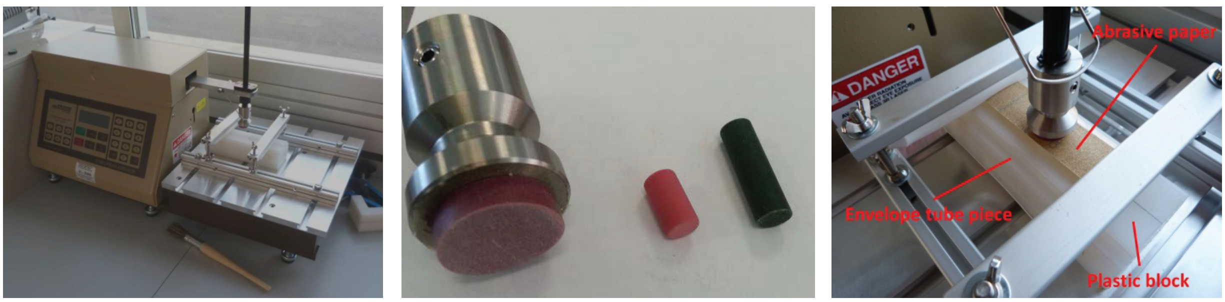

Fig. 5: a) Taber Linear Abraser – Model 5750, b) left: abrasor CS-10F (3/4”), middle: MIL 12397 Erasor (1/4”), right: CS 10 (1/4”), c) abradant shaping with abrasive paper

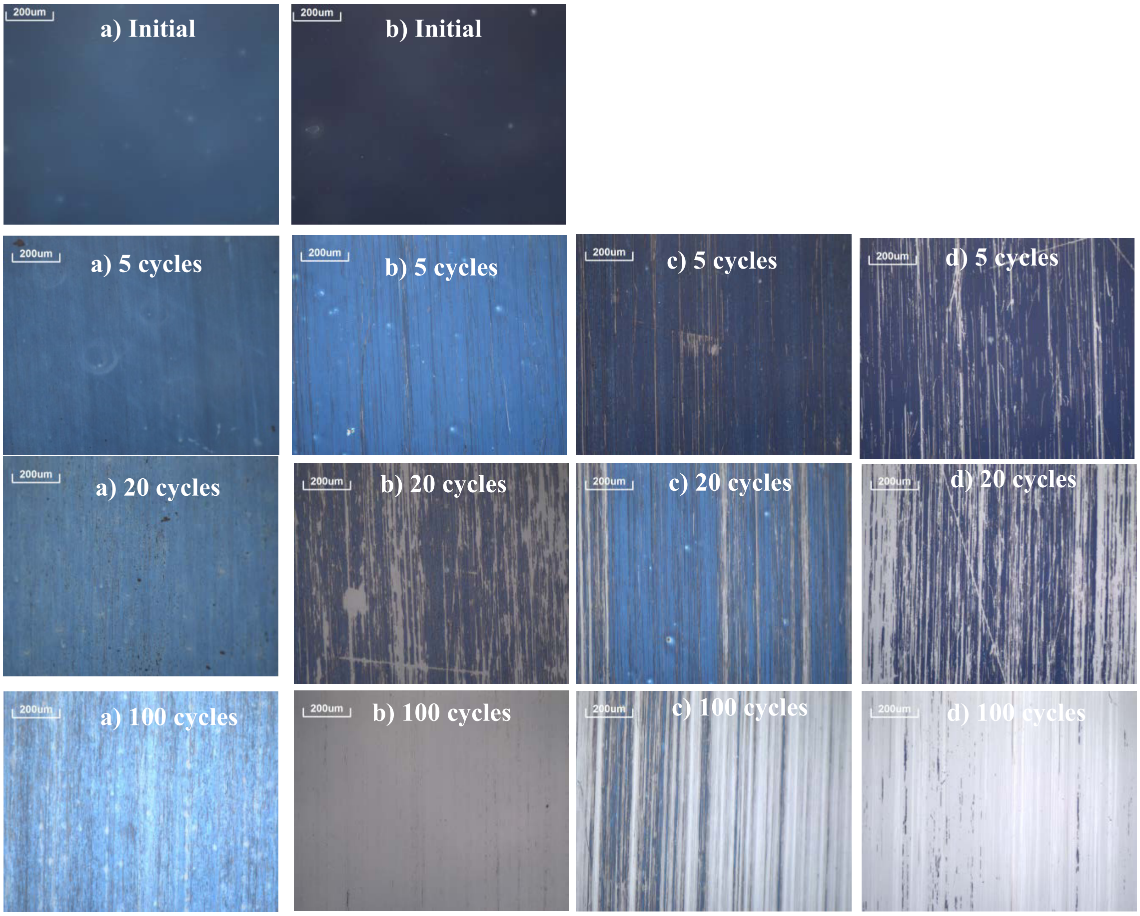

Fig. 6: a) Coating A using MIL 12397 Erasor (1/4"), b) Coating B using MIL 12397 Erasor (1/4"), c) Coating A using abrasor CS 10 (1/4"), d) Coating B using abrasor CS 10 (1/4"). The blue color indicates AR-coating, the white color indicates removal of the AR-coating.

The stroke length is set to 38.1 mm. No additional weights are installed and the total mass of the combination of arm and abradant is 295 g. The velocity of the moving arm is 25 cycles per minute. The abrasive effect of three different abradants has been examined by microscopic inspection. The abradants used are: the Erasor according to MIL 12397 with diameter of ¼" (very mild abrading action), the abrasor CS-10 with diameter of ¼" (mild-medium abrading action) and the abrasor CS-10 F with diameter ¾" (mild abrading action) (see Fig. 5b). Taber Industries recommends to use abradants of diameter ¾ " only on flat surfaces. However, usage of abradants of ¾ " is desirable as the measurement spot of the transmittance measurement system used is smaller than ¾ " but larger than ¼ ". Thus an attempt to shape the abradant to match the sample surface geometry using an abrasive paper attached to a glass envelope tube sample of the same geometry has been made. With this method a homogeneous contact between sample and abradant across the entire diameter is achieved (see Fig. 5b).

The microscopic images reveal that the abrasion caused by the MIL 12397 Erasor is milder and more homogeneous than for the CS10 abrasor (see Fig. 6). After 500 cycles of testing with the MIL 12397 Erasor there is still anti-reflective coating remaining on the glass substrate for coating A, while coating B is already completely removed after 100 cycles. The CS10 abrasor removes a stripe pattern of coating A, while the MIL 12397 Erasor causes a soft and homogeneous abrasion effect. For coating B, the MIL 12397 Erasor also removes a stripe pattern, very similar to the abrasion caused by the CS10 abrasor. Due to the more homogeneous performance for coating A, the MIL 12397 Erasor seems more appropriate to test anti-reflective coatings of glass tubes than the CS10 abrasor.

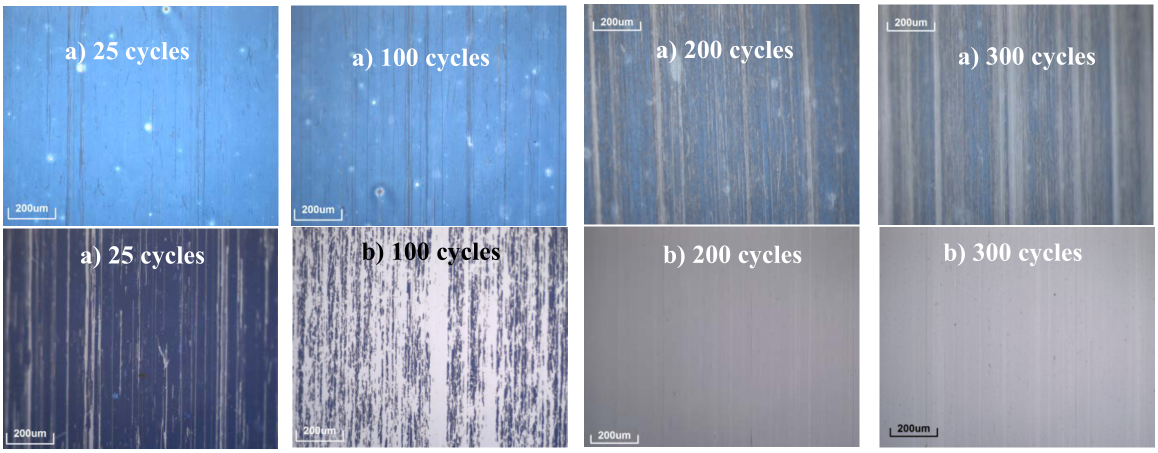

Fig. 7: a) Coating A using abrasor CS-10F (3/4"), b) Coating B using abrasor CS-10F (3/4")The blue color indicates AR-coating, the white color indicates removal of the AR-coating.

The CS-10F abrasor of diameter ¾" is the mildest available in its size. In contrast to the MIL 12397 Erasor it contains abrasive grain in the rubber matrix, which leads to the removal of a stripe pattern for coating A (see Fig. 7). However due to the three times larger diameter, the normal force is reduced to one ninth. This leads to an overall milder abrasive effect of the CS-10F (¾") compared to MIL 12397 Erasor (which is only available in ¼" size): after 100 cycles there are still parts of the anti-reflective-coating B remaining, while as when using the MIL 12397 Erasor 100 cycles lead already to the complete removal of coating B (compare also transmittance measurements in Fig. 8).

It can be concluded that both, the MIL 12397 Erasor (¼") and the CS-10F (¾") are suited to test anti-reflective coatings. The discussion of which one should be used is still ongoing with standardization committees and industry partners. The benefit of using the MIL 12397 Erasor is that it contains no abrasive grain. This leads to a homogeneous abrasion of coating A. However for coating B, a stripe pattern similar to the CS-10F is removed, whereas the CS-10F has a milder effect due to its larger diameter. The benefit of using the CS-10F with ¾" diameter is that the abraded surface is larger than the measuring spot of the commonly used Perkin Elmer spectrophotometer.

to measure the transmittance of the samples. The measuring spot of the spectrophotometer with integrating sphere attachment is approximately 9 x 17 mm². Thus, when using abrasors of diameter ¼", the sample needs to be rotated in order to achieve a larger tested surface than the measuring spot. Manual alignment will always contain errors and overlapping of abraded surface in some areas is not avoidable. On the other hand usage of ¾" CS-10F abradant leads to non-homogeneous abrasion at the borders of the contact surface. However, at the centre of the tested surface a homogeneously abraded surface is achieved, which is larger than the measuring spot of the spectrophotometer. This can be seen in Fig. 8, where reproducible transmittance measurements are obtained for both methods.

5. Summary

This paper presents accelerated aging tests on parabolic trough receivers. In the overheating test a parabolic trough receiver is heated above operating temperature and changes in heat loss and optical efficiency are measured. Lifetime predictions using the Arrhenius equation require extensive testing and are planned for the future. Simplified tests were performed by heating receivers to 478 °C for 1000 hours. First tests lead to the introduction of a general heat up speed limit of +5 K/min and a heat up limit of + +0.05 K/min for the first heat up above 400 °C.

In a thermal cycling test receivers were cycled from 200 °C to 478 °C for 100 times. A bellow fatigue test allows for the mechanical cycling of the bellow compression and expansion cycle. Here in a typical test receivers are subjected to 20,000 cycles and rested for a 24 hour waiting period. The receiver test was considered passed, if heat loss during the test had not increased for more than 30 %. As the bellow fatigue test needed refinement, a second version of the bellow fatigue test is currently under construction.

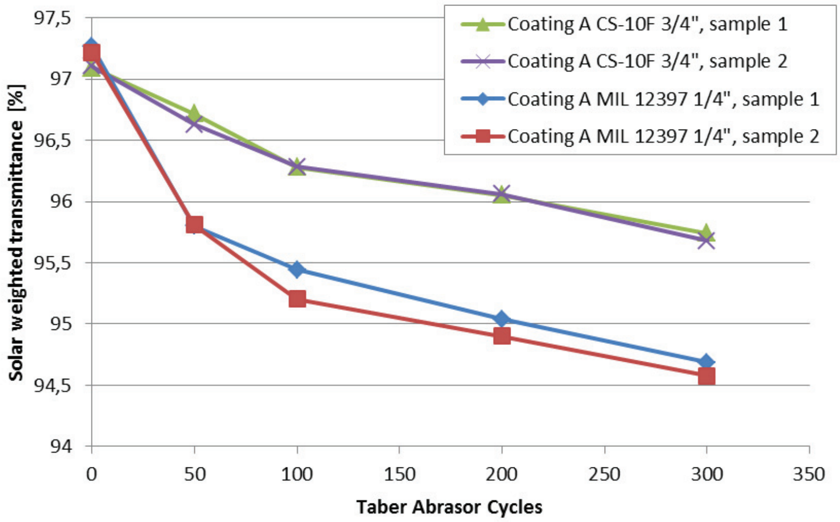

Fig. 8: Solar weighted transmittance of Coating A in the Linear Abrasor Test using the CS-10F (¾") and MIL 12397 Eraser (¼") .

In a thermal cycling test receivers were cycled from 200 °C to 478 °C for 100 times. A bellow fatigue test allows for the mechanical cycling of the bellow compression and expansion cycle. Here in a typical test receivers are subjected to 20,000 cycles and rested for a 24 hour waiting period. The receiver test was considered passed, if heat loss during the test had not increased for more than 30 %. As the bellow fatigue test needed refinement, a second version of the bellow fatigue test is currently under construction.

Furthermore, using the Taber Linear Abrasor, abrasion tests were performed on two different anti-reflective coatings and using the CS-10F rubber (¾") and MIL 12397 Eraser (¼"). As transmittance is measured with spectrophotometer with an illuminated spot of ca. 9 mm x 17 mm, the lager diameter of the CS-10F rubber offers the advantage that test can be performed without having to do multiple abrading stripes next to each other. The usage of the CS-10F rubber (¾") is being discussed with industry and in standardization committees.

Lifetime predictions remain a challenge and guide the way for the next steps: In the overheating test the application of the Arrhenius equation should be tested for its usefulness in standardized testing of full receivers. The thermal cycling test presented in this paper is performed with only few cycles and slow cool down, but at very high temperature. A high power heating and cooling can lead to more realism there. For the bellow test bench the influence of temperature at the bellow and cycle-frequency on lifetime should be further investigated. The abrasion test uses a rubber with or without abrasion grain instead of a simulated sand storm or a high pressure water jet simulating the cleaning. Yet, in component testing there has to be a compromise found between testing price, testing time and transferability to the field – or between realism and simplicity. However, the tests presented in this paper have been used in measurements for industry and showed to be useful for ranking parabolic trough receiver durability.

Acknowledgements

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References

[1] Sanchez M, Mateu E, García P, Villuendas F, Heras C, Alonso R. Optical and thermal characterization of solar receivers for parabolic trough collectors, Proceedings of SolarPACES Conferences, Perpignan, 2010.

[2] Lei D, Li Q, Wang Z, Li J, Li J. An experimental study of thermal characterization of parabolic trough receivers, Energy Conversion and Management 69, 2013, pp. 107-115

[3] Burkholder F, Kutscher C. Heat loss testing of Schott's 2008 PTR70 Parabolic Trough Receiver, National Renewable Energy Laboratory Technical Report, NREL/TP-550-45633, 2009.
[4] Pernpeintner J. Schiricke B, Lüpfert E, Lichtenthäler N, Macke A, Wiesemeyer K. Combined measurement of thermal and optical properties of receivers for parabolic trough collectors, Proceedings of SolarPACES Conferences, Berlin, 2009.
[5] Kutscher C, Netter J. A method for measuring the optical efficiency of evacuated receivers, Journal of Solar Energy Engineering, Feb. 2014, Vol. 136
[6] Chiarappa T, Maccari A, Matino F, Raggi C. A new glass-to-metal seal and a real operating condition accelerated test, Proceedings of SolarPACES Conferences, Marrakesch, 2012
[7] Brunold S, Frei U, Carlsson B, Möller K, Köhl M. Accelerated life testing of solar absorber coatings: testing procedure and results, Solar Energy Vol. 68, pp. 313-323, 2000